PATENT

ALUMINUM-COPPER-MAGNESIUM ALLOYS HAVING ANCILLARY ADDITIONS OF LITHIUM

BACKGROUND OF THE INVENTION

This invention relates to aluminum-copper-magnesium alloys having ancillary additions of lithium in order to decrease density while at the same time increasing strength, toughness, and especially fatigue crack growth resistance of the aluminum-copper-magnesium alloy. These alloys are useful in aerospace applications, for example.

It is generally well known in the aerospace industry that one of the most effective ways to reduce the weight of an aircraft is to reduce the density of aluminum alloys used in aircraft construction. This desire led to the addition of lithium, the lowest density metal element, to aluminum alloys. Aluminum Association ("AA") alloys, such as 2090 and 2091 contained about 2.0 wt % lithium, which translated into about a 7% weight savings over alloys containing no lithium. Another aluminum alloy, AA 8090 contained about 2.5 wt % lithium, which translated into an almost 10% weight savings over alloys without lithium.

Molten lithium, however, is a highly reactive and highly aggressive material, which is difficult to handle and which is also difficult to alloy with the base alloy. Because of its high reactivity, any moisture in the presence of the molten aluminum-lithium can cause explosions. In addition, because of its highly aggressive nature, special refractories must be used in casting the lithium alloys.

Because the propensity for explosions of molten aluminum-lithium is reduced as the weight percent of lithium is reduced, it is desired to reduce lithium levels. However, it is also desirable to maintain the properties of less density, greater strength and increased fatigue crack growth

resistance at the same time. Of course, it was known that reductions in the weight percent of lithium would result in less weight savings, but this tradeoff was made in order to reduce the difficulty of making the aluminum-lithium alloys.

United States Patent No. 5,455,003 discloses aluminum-copper-lithium alloys with improved cryogenic fracture toughness. Of major importance in cryogenic applications are high strength and high fracture toughness. These properties are obtained by artificially aging the aluminum alloy. However, this aging will have a detrimental effect on fatigue crack growth resistance. In damage tolerant applications in aircraft, fatigue crack growth resistance is very important. Better fatigue crack growth resistance means that cracks will grow slower, thus making airplanes much safer because small cracks can be detected before they achieve critical size for catastrophic propagation. Furthermore, slower crack growth can have an economic benefit due to the fact that longer inspection intervals can be utilized.

What is needed, therefore, is an aluminum alloy useful for, among other things, damage tolerant applications in aircraft which has not only low density, high strength and good fracture toughness, but also excellent fatigue crack growth resistance.

SUMMARY OF THE INVENTION

The aluminum alloy of the invention has met or exceeded the above-mentioned needs as well as others. The aluminum alloy comprises up to about 4.5 wt % copper; from about 0.6 to 6.0 wt % magnesium; and from about 0.01 to 1.0 wt % lithium. It has been found, quite surprisingly and unexpectedly, that the ancillary additions of low levels of lithium to aluminum-copper-magnesium alloys provided a high strength, low density material that exhibited good fracture toughness and improved fatigue crack growth resistance over prior art aluminum-copper-magnesium alloys.

BRIEF DESCRIPTION OF THE DRAWINGS

A full understanding of the invention can be gained from the following detailed description of the invention when read in conjunction with the accompanying drawings in which:

Figure 1A is a graph showing the composition space covering aluminum-copper-magnesium alloys with ancillary lithium additions.

Figure 1B is a chart showing the tensile yield strength of various specimens made from aluminum alloys containing aluminum-copper-magnesium alloys designated Alloy A, Alloy B, Alloy C and Alloy D after being subjected to different aging conditions.

Figure 2 is a bar graph showing the improvement in specific strength for some of the specimens shown in Figure 1.

Figure 3 is a graph showing the typical representation of fatigue crack growth performance rate da/dn (*in/cycle*) and how it changes with performance improvements.

Figure 4 is a graph showing the fatigue crack growth curves for (1) Alloy A-T3 plate; (2) Alloy C-T3 plate; and (3) Alloy D-T3 plate.

Figure 5 is a graph showing the fatigue crack growth curves for (1) Alloy A-T39 plate; (2) Alloy C-T39 plate; and (3) Alloy D-T39 plate.

Figure 6 is a graph showing the fatigue growth curves for (1) Alloy A-T8 plate; (2) Alloy C-T8 plate; and (3) Alloy D-T8 plate.

Figure 7 is a bar graph showing the percentage change in da/dn at $\Delta K = 10$ Ksi $(in)^{1/2}$.

Figure 8 is a graph showing the fracture toughness R-curves of Alloy A-T3 and Alloy C-T3.

Figure 9 is a graph showing the fracture toughness R-curves of Alloy A-T39, Alloy C-T39 and Alloy D-T39 plate.

DETAILED DESCRIPTION

For the description of alloy compositions that follow, all references are to weight percentages (*wt %*) unless otherwise indicated. When referring to any numerical range of values, such ranges are to be understood to include each and every number and/or fraction between the stated range minimum and maximum. A range of about 0.01 to 0.99 wt % lithium, for example, would include all intermediate values of about 0.02, 0.03, 0.04 and 0.1 wt % all the way up to and including .97, .98 and .9895 wt % lithium. The same applies to the other elemental ranges set forth below. The term *"substantially free"* means having no significant amount of that component purposely added to the alloy composition, it being understood that trace amounts of incidental elements and/or impurities may find their way into a desired end product.

As used herein, the term *"damage tolerant aircraft part"* means any aircraft or aerospace part which is designed to ensure that its crack growth life is greater than any accumulation of service loads which could drive a crack to a critical size resulting in catastrophic failure. Damage tolerance design is used for most of the primary structure in a transport category airframe, including but not limited to fuselage panels, wing boxes, horizontal and vertical stabilizer boxes, pressure bulkheads, and door and window frames. In inspectable areas, damage tolerance is typically achieved by redundant designs for which the inspection intervals are set to provide at least two inspections per number of flights or flight hours it would take a visually detectable crack to grow to its critical size.

The present invention relates to an aluminum-copper-magnesium alloy having ancillary additions of lithium. In accordance with the invention, a wrought aluminum-copper-magnesium-lithium alloy is provided which has improved strength, fracture toughness and fatigue crack growth

resistance over prior art aluminum-copper-magnesium alloys. The alloys of the present invention are especially useful for damage tolerant aircraft parts, such as lower wing sections, because of the surprising and unexpected increase in fatigue crack growth resistance over prior art aluminum-copper-magnesium alloys. Because of the addition of low levels of lithium additions, the problems of higher (*i.e., over 1.5 wt % lithium*) additions of lithium, such as explosions of the molten metal, are reduced or eliminated.

The compositional ranges of the main alloying elements (*copper, magnesium and lithium*) of the improved alloy of the invention are broadly defined as follows: (1) up to 4.5 wt % copper; (2) from about .6 to 6.0 wt % magnesium; and (3) from about 0.01 to 0.99 wt % of lithium. The balance of the aluminum alloy of the invention contains aluminum and incidental impurities.

In addition to aluminum, copper, magnesium and lithium, the alloys of the present invention can contain dispersoids selected from the group consisting of chromium, vanadium, titanium and zirconium and mixtures thereof in the range of about 0.0 to 0.6 wt % and/or dispersoids such as manganese, nickel, iron, hafnium and scandium and mixtures thereof in the range of 0 to 1 wt %. Other alloying elements, such as zinc, silver and silicon and mixtures thereof in amounts up to about 2.0 wt % can also be added.

The copper is added to increase the strength of the aluminum base alloy. Care must be taken, however, to not add too much copper since the corrosion resistance can be reduced. Also, copper additions beyond maximum solubility can lead to low fracture toughness and low damage tolerance.

The magnesium is added to provide strength and reduce density. Care should be taken, however, to not add too much magnesium since magnesium additions beyond maximum solubility will lead to low fracture toughness and low damage tolerance.

The lithium is added to reduce density and to increase strength. Care should be taken, however, in not adding too much lithium since exceeding the maximum solubility will lead to low fracture toughness and low damage tolerances. Lithium additions in amounts of about 1.5 wt % and above result in the formation of the δ′ (*"delta prime"*) phase with composition of Al_3Li. The presence of this phase, Al_3Li, is to be avoided in the alloys of the present invention.

The interaction of lithium atoms in supersaturated solid solution, with atoms of magnesium and/or copper appear to give rise to the formation of clusters of atoms of solute. This behavior is observed by the appearance of diffuse scatter in electron diffraction images. This behavior, which was not expected and is surprising, is apparently responsible for the improvements in fatigue performance of the alloys of the invention, which will be discussed below.

It has been found, quite unexpectedly and surprisingly, that the combination of lower copper levels, higher magnesium levels and lower levels of lithium give a surprisingly strong, less dense aluminum alloy which has superior fatigue crack growth resistance. Fatigue crack growth resistance is a critical property for damage tolerant aircraft parts, such as fuselage sections and lower wing sections. As is known, these parts of an aircraft are subject to cyclical stresses, such as the fuselage skin which is expanded and contracted upon pressurization and depressurization of the aircraft cabin and the lower wing skin which experiences tensile stresses in flight and compressive stresses while the aircraft is on the ground. Improved fatigue crack growth resistance means cracks will grow and reach their critical dimension more slowly. This allows longer inspection intervals to be used, thus reducing aircraft operating cost. Alternatively, the applied stress could be raised while keeping the same inspection interval, thereby reducing aircraft weight.

Returning now to a discussion of the alloy composition of the invention, it should be noted that the copper and magnesium in the compositional ranges set forth above will be soluble in the alloy. This is important in that atoms of the alloying elements in solid solution or forming clusters translate to increased fatigue crack growth resistance, which is, as was mentioned above, a critical property for damage tolerant aircraft parts.

Referring now to Figure 1A, the broad, preferred, more preferred and most preferred ranges for the copper and magnesium contents of the aluminum alloy of the invention will be discussed. For all of these copper and magnesium ranges, the range of the lithium content is from about 0.01 to 0.99 wt %. A benefit has been observed when the lithium concentration is above 0.25 and even 0.35 and up to 0.95. The lithium concentration will vary depending on the desired level of improved performance of the wrought product. The combination of copper, magnesium and lithium needs to be carefully considered as to not exceed maximum solubility. The following composition ranges were selected using a combination of phase diagram data from thermodynamic equilibrium and experimental results.

Turning now to Figure 1A, it can be seen that the broad ranges for copper and magnesium fall within a closed area on a graph with wt % copper on the x-axis and wt % magnesium on the y-axis, the closed area being bounded by generally straight lines joining the following points:

POINT A = 0 Cu. 0.6 Mg
POINT B = 4.5 Cu, 0.6 Mg
POINT C = 4.5 Cu, 6.0 Mg
POINT D = 0 Cu, 6.0 Mg
and back to POINT A.

The preferred ranges for copper and magnesium are defined by a closed area on a graph with wt % copper on the x-axis and

wt % magnesium on the y-axis, the closed area being bounded by generally straight lines joining the following points:

POINT A = 0 Cu, 0.6 Mg
POINT B = 4.5 Cu, 0.6 Mg
POINT E = 4.5 Cu, 2.3 Mg
POINT F = 2.0 Cu, 6.0 Mg
POINT D = 0 Cu, 6.0 Mg
and back to POINT A.

The more preferred ranges for copper and magnesium are defined by a closed area on a graph with wt % copper on the x-axis and wt % magnesium on the y-axis, the closed area being bounded by generally straight lines joining the following points:

POINT A - 0 Cu, 0.6 Mg
POINT B = 4.5 Cu, 0.6 Mg
POINT G = 1.5 Cu, 6.0 Mg
POINT D = 0 Cu, 6.0 Mg
and back to POINT A.

Finally, the most preferred ranges for copper and magnesium are defined by a closed area on a graph with wt % copper on the x-axis and wt % magnesium on the y-axis, the closed area being bounded by generally straight lines joining the following points:

POINT A = 0 Cu, 0.6 Mg
POINT B = 4.5 Cu, 0.6 Mg
POINT H = 4.5 Cu, 2.0 Mg
POINT I = 0 Cu, 2.0 Mg
and back to POINT A.

It will be appreciated that the equation for straight line 1 on Figure 1A (*between Points E and F*) can be expressed as follows:

$$Cu=\frac{-2.5}{3.7}(Mg-6)+2$$

and the equation for straight line 2 (*between Points B and G*) can be expressed as the following equation:

$$Cu=\frac{-3}{5.4}(Mg-6)+1.5$$

The following example sets forth alloys and resulting wrought products made in accordance with the invention.

EXAMPLE

An ingot of an aluminum-copper-magnesium alloy having the following composition was cast:

INGOT NO. 1

Si	Fe	Cu	Mn	Mg	Zn	Zr
0.03	0.03	3.24	0.58	1.32	-0-	0.11

(*Remainder is aluminum and incidental impurities.*)

Material fabricated from this ingot will be designated Alloy A hereinafter in this Example.

After this, the remaining molten metal was re-alloyed (*i.e., alloying again an alloy already made*) by adding 0.25% lithium to create a target addition of 0.25 wt % lithium. A second ingot was then cast having the following composition:

INGOT NO. 2

Li	Si	Fe	Cu	Mn	Mg	Zn	Zr
0.19	0.03	0.04	3.41	0.61	1.28	-0-	0.1

(*Remainder is aluminum and incidental impurities.*)

Material fabricated from this ingot will be designated Alloy B hereinafter in this Example.

Ingot No. 3 was created by re-alloying the remaining molten metal after casting Ingot No. 2 and then adding another 0.25 wt % lithium to create a total target addition of 0.50 wt % lithium. Ingot No. 3 had the following composition:

INGOT NO. 3

Li	Si	Fe	Cu	Mn	Mg	Zn	Zr
0.35	0.04	0.04	3.37	0.6	1.2	-0-	0.11

(Remainder is aluminum and incidental impurities.)

Material fabricated from this ingot will be designated Alloy C hereinafter in this Example.

Ingot No. 4 was created by re-alloying the remaining molten metal after casting Ingot No. 3 and then adding another 0.25 wt % lithium to create a total target addition of 0.75 wt % lithium. A fourth ingot was cast having the following composition:

INGOT NO. 4

Li	Si	Fe	Cu	Mn	Mg	Zn	Zr
0.74	0.02	0.03	3.34	0.56	1.35	0.01	0.12

(Remainder is aluminum and incidental impurities.)

Material fabricated from this ingot will be designated Alloy D hereinafter in this Example.

The four ingots were stress relieved and homogenized. The ingots were then subjected to a standard presoak treatment after which the ingots were machine scalped. The scalped ingots were then hot rolled into four (4) separate 0.7 inch gauge plates using hot rolling practices typical of *2XXX* alloys.

After the four (4) separate plates were produced, a section of each of the plates was removed. Each of the four (4) sections were (a) solution heat treated; (b) quenched; and (c) stretched 1.5%. After this, eight (8) tensile strength test samples were produced from each of the

treated four (4) sections, making a total of thirty-two (32) tensile strength test samples. One tensile strength test sample from each group of eight (8) (*there being a total of four (4) plates in each group*) was each subject to eight (8) different aging conditions, as described in the legend of Figure 1. After this, tensile yield strength tests were performed, with the results being shown in Figure 1B. It will be seen that the alloys having lithium additions exhibited greater strength than those without lithium, while at the same time exhibiting thermal stability.

After this, the remainder of three of the four plates (*i.e., Ingot No. 1 plate, Ingot No. 3 plate and Ingot No. 4 plate*) was each cut into thirds (*1/3rds*), to form pieces 1, 2 and 3 for each plate, or a total of 9 pieces. Piece 1 of all three plates were (a) solution heat treated; (b) quenched; (c) stretched 1 1/2%; and (d) aged to T8 temper by aging it 24 hours @ 350°F. These pieces were designated Alloy A-T8; Alloy C-T8; and Alloy D-T8. Piece 2 of all three plates were (a) solution heat treated; (b) quenched; (c) stretched 1 1/2%; and (d) naturally aged to T3 temper. These pieces were designated Alloy A-T3; Alloy C-T3; and Alloy D-T3. Finally, Piece 3 of all three plates were (a) solution heat treated; (b) quenched; (c) cold rolled 9%; (d) stretched 1 1/2%; and (e) naturally aged. These pieces were designated Alloy A-T39; Alloy C-T39; and Alloy D-T39. It was these pieces which provided the material for all of the further testing which will be reported herein.

Referring now to Figure 2, the tensile yield strength divided by density for a testing portion of each of the nine (9) pieces produced above is shown. It can be seen that improvements in the tensile yield strength to density ratio were found for ancillary lithium additions.

Referring now to Figures 3-7, the key property of fatigue crack growth resistance will now be discussed. Figure 3 is a graph showing the typical representation of

fatigue crack growth performance and how improvements therein can be shown. The x-axis of the graph shows the applied driving force for fatigue crack propagation in terms of the stress intensity factor range, ΔK, which is a function of applied stress, crack length and part geometry. The y-axis of the graph shows the material's resistance to the applied driving force and is given in terms of the rate a which a crack propagates, da/dn in inch/cycle. Both ΔK and da/dn are presented on logarithmic scales as is customary. Each curve represents a different alloy with the alloy having the curve to the right exhibiting improved fatigue crack growth resistance with respect to the alloy having the curve to the left. This is because the alloy having the curve to the right exhibits a slower crack propagation rate for a given ΔK which represents the driving force for crack propagation.

Turning to Figures 4-6, it can be seen, that based on the criteria discussed with respect to Figure 3, the addition of lithium substantially increases the fatigue crack growth resistance in the respective alloys in the T3 and T39 conditions. The fatigue crack rates for crack driving forces of ΔK equal to 10 Ksi $(\text{in})^{1/2}$ are summarized in Figure 7. The percentage improvement in fatigue crack growth resistance (*i.e., percentage reduction in fatigue crack growth rates*) is given at the top of the graph. Alloy C-T3 and Alloy D-T3 show improvements of 27% and 26%, respectively over Alloy A-T3 (*no lithium additions*). The percentage improvements in fatigue crack growth resistance of Alloy C-T39 and Alloy D-T39 over Alloy A-T39 (*no lithium additions*) was 67% and 47% respectively.

With regard to the T8 alloys, it can be seen that the lithium additions do not improve the fatigue crack growth resistance. In the case of artificially aged alloys, aged to peak strength, the only advantage of lithium additions is in terms of additional strength and lower density.

Figures 8 and 9 show the fracture toughness R-curves for the T3 and T39 tempers, respectively. The R-curve is a measure of resistance to fracture (K_R) versus stable crack extension (Δaeff). In addition, the following table shows single-point measurements of fracture toughness for Alloys A, C and D in the T3, T39 and T8 tempers in terms of K_{R25}, which is the crack extension resistance, K_R, on the R-curve corresponding to the 25% secant offset of the test record of load versus crack-opening displacement (COD), and Kq, which is the crack extension resistance corresponding to the 5% secant offset of the test record of load versus COD. K_{R25} is an appropriate measure of fracture toughness for moderate strength, high toughness alloy/tempers such as T3 and T39, while Kq is appropriate for higher strength, lower toughness alloy/tempers such as T8.

TABLE

Strength And Toughness Measurements
(Tensile Longitudinal Properties - Toughness Orientation L-T)

Alloy/Temper	TYS (Ksi)	UTS (Ksi)	Elongation (%)	Kq (Ksi $in^{1/2}$)	KR 25 (Ksi $in^{1/2}$)
Alloy A-T3	47.7	65.6	18.6	-	97.9
Alloy C-T3	51.4	69.8	17.1	-	107.8
Alloy D-T3	51.1	70.6	17.5	-	NOT TESTED
Alloy A-T39	61.2	67.3	11.4	-	88.8
Alloy C-T39	63.3	70.7	9.3	-	91.5
Alloy D-T39	65.7	70.5	9.9	-	97.5
Alloy A-T8	63.7	69.7	12.1	32.4	-
Alloy C-T8	65.9	71.9	11.7	38.7	-
Alloy D-T8	67.8	73.8	10.7	38.9	-

natural aging

artificial aging

It will be appreciated that fracture toughness is somewhat improved by the lithium additions. Moreover, it should be noted that lithium additions yielded improved toughness at a higher strength level. Therefore, the strength/toughness relationship was significantly improved.

This was unexpected because lithium additions are well known to decrease fracture toughness. However, it should be noted that the lithium additions yielded higher strength. Therefore, the strength/toughness relationship was improved.

While specific embodiments of the invention have been disclosed, it will be appreciated by those skilled in the art that various modifications and alterations to those details could be developed in light of the overall teachings of the disclosure. Accordingly, the particular arrangements disclosed are meant to be illustrative only and not limiting as to the scope of the invention which is to be given the full breadth of the appended claims and any and all equivalents thereof.